The Viscoelastic Properties of Wood Used for the Musical Instruments I

The Viscoelastic Properties of Wood Used for the Musical Instruments I*

Tsutomu AOKI** and Tadashi YAMADA**

Abstract——This study deals with the viscoelastic properties of wood used for the musical instruments and various other species. The properties were measured by composite oscillator at 60 kHz, vibrating reed at 55~65 Hz, and stress relaxation over the time range of 10 to 1000 sec. The results are summarized as follows:

(1) There observed the two major frequency dispersions for wood in radial and tangential directions. The dispersion in very low frequency range is probably due to the movement of rather large segments of the structures, while that of high frequency range may be asociated with the motion of methylol groups in the non-crystalline region of wood substance.

(2) The values of the dynamic loss modulus of hardwood in tangential direction increased linearly with increasing ρ in linear scale up to $\rho=1.3$. On the other hand, the values in radial direction increased linearly with ρ up to $\rho=0.7$ and then remained almost constant above $\rho=0.7$.

(3) The values of the dynamic loss modulus did not change by the extraction.

(4) The values of the dynamic elastic modulus and loss modulus for wood used for the musical instruments (Sitka spruce and Yezo spruce) were larger than those of other species in the longitudinal direction.

Introduction

In order to make clear the acoustic properties of wood there are many problems which must be solved. This paper deals with the viscoelastic properties of wood since these properties seem to be concerned with the acoustic properties such as attenuation coefficient and acoustic absorptivity.

There are few studies discussed the dynamic mechanical properties of wood in relation to the static ones, especially the dynamic loss modulus in the transverse directions.

The following four points are discussed in this paper.

1) The frequency dependences of the dynamic mechanical properties of wood in the transverse directions.

2) The effects of specific gravity and grain angle on the dynamic mechanical properties of wood.

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3) The influence of the extraction on the dynamic mechanical properties of wood.

4) On the dynamic properties of wood used for the musical instruments.

Experimental

The wood samples used are shown in Table 1. All the measurements were carried out at 20±1°C and 50±5% R.H.

Table 1. Samples used for the dynamic measurements.

Balsa (*Ochroma* sp.)	B
Kiri (*Paulownia tomentosa* STEUD,)	C
Sugi (*Cryptomeria japonica* D. DON)	A
Nezuko (*Thuja standishii* CARR.)	A
Kusunoki (*Cinnamomum camphora* SIEB.)	B
Shiinoki (*Castanopsis cuspidata* SCHOTTKY)	D
Karamatsu (*Larix leptolepis* GORDON)	A
Hoonoki (*Magnolia obovata* THUNB.)	B
Yamaguruma (*Trochodendron aralioides* SIEB. et ZUCC.)	D
Ichii (*Taxus cuspidata* SIEB. et ZUCC.)	A
Hinoki (*Chamaecyparis obtusa* SIEB. et ZUCC.)	A
Tsuga (*Tsuga sieboldii* CARR.)	A
Kuri (*Castanea crenata* SIEB. et ZUCC.)	C
Buna (*Fagus crenata* BL.)	B
Mizuki (*Cornus controversa* HEMSL.)	B
Aogiri (*Firmiama platanifolia* SCHOTT et ENDL.)	C
Uwamizuzakura (*Prunus grayana* MAXIM.)	B
Harunire (*Ulmus davidiana* PLANCH var *japanica* NAKAI)	C
Keyaki (*Zelkowa serrata* MAKINO)	C
Yachidamo (*Fraxinus mandshurica* RUPR. var *japonica* MAXIM.)	C
Konara (*Quercus serrata* THUNB.)	C
Mizume (*Betula grossa* SIEB. et ZUCC.)	B
Shirakashi (*Quercus myrsinaefolia* BLUME)	D
Isunoki (*Distylium racemasum* SIEB. et ZUCC.)	B
Burman timber	B
Gray birch (*Betula* sp.)	B
Shimakokutan (*Diospyros* spp.)	B

A: coniferous wood. B: diffuse porous wood. C: ring porous wood. D: others.

A composite oscillator (longitudinal vibration) was employed for the measurement of the dynamic properties at 60 kHz. The dimensions of specimens were $0.5\times0.5\times1.0\sim1.7$ cm (radial and tangential directions) and $0.5\times0.5\times3.4\sim4.7$ cm (longitudinal direction). The values of dynamic elastic modulus E', loss tangent

$\tan\delta$ and dynamic loss modulus E'' were calculated by the following equations:

$$E' = 4 \times l^2 \times \rho \left\{ f_0 - (f_r - f_0)\frac{m_1}{m_2} \right\}^2,$$

$$\tan\delta = \frac{\left(1 + \frac{m_1}{m_2}\right)\Delta f_0}{f_0},$$

$$E'' = E' \times \tan\delta,$$

where, l, m_2, ρ are the length, the mass and the density of the specimen, and m_1, f_r are the mass (2.990 g) and the resonant frequency (59.955 kHz) of the quartz crystal, f_0 is the resonant frequency of composite oscillator (specimen and quarzt crystal), and Δf_0 is the frequency defference between the points at which the value of AC resistance between the crystal electrodes becomes twice that of resonance.

The vibrating reed method was adopted for the measurements at 55~65 Hz. The dimensions of the specimens were $0.1 \times 0.5 \times 4.5 \sim 7.0$ cm. E', $\tan\delta$ and E'' were calculated from the following equations:

$$E' = \frac{B_n \times l^4 \times \rho \times f_r^2}{d^2},$$

$$\tan\delta = \frac{\Delta f_r}{f_r},$$

$$E'' = E' \times \tan\delta,$$

where l, d, ρ are the length, the depth and the density of the specimen, and f_r is the resonant frequency, and Δf_r is the half width of resonance curve and B_n (=38.4) is the constant which depends on the vibration mode, respectively.

The valuse of $\tan\delta$ and E'' at 10, 10^2 and 10^3 sec were calculated by the following equations:

$$\tan\delta = \frac{\alpha}{2\pi},$$

$$E'' = E' \times \tan\delta,$$

where α is the slope of stress relaxation curve in logarithmic scales.

The values of E', E'' and $\tan\delta$ at 10, 10^2 and 10^3 sec were estimated from data on stress relaxation reported previously[1)].

Results and Discussion

1. The frequency dependences of the dynamic mechanical properties of wood in the transverse directions

There are few data on the frequency dependence of dynamic mechanical properties in the transverse directions. In this section, the frequency dependences of the dynamic properties of wood are discussed.

Figs. 1～3 show the dynamic mechanical properties as a function of frequency. The value of E' increased slightly with increasing frequency. The inflection point appeared in the range of 10 to 10^{-1} Hz in both radial (R-) and tangential (T-) directions may be due to the different modes of vibration.

The two major dispersions were observed as shown in Fig. 2; one began above 10^2 Hz and the other below 10^{-2} Hz.

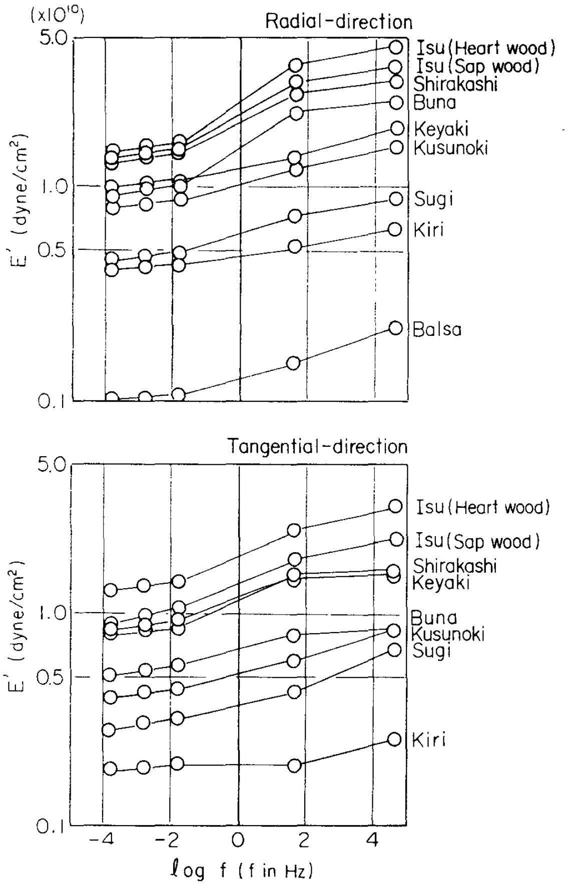

Fig. 1. E' as a function of frequency in the transverse directions.

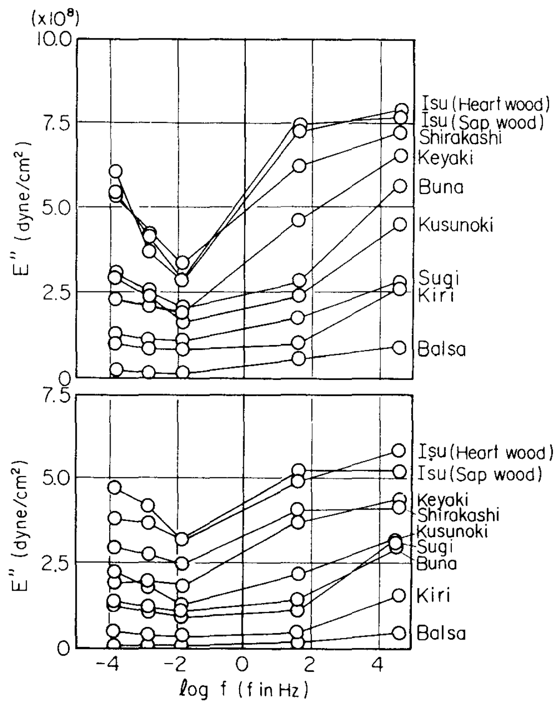

Fig. 2. E'' as a function of frequency in radial direction (upper) and tangential direction (under).

Pentoney et al.[2,3] found the two mechanical dispersions in longitudinal (L-) direction; one began above 10^3 Hz and the other below 10^{-2} Hz. Holz[4] obtained a mechanical dispersion beginning 10^3 Hz, and Tatemiti[7] found the same dispersion.

On the other hand, Fukada[5] observed a temperature dispersion at -100°C and 500 Hz, and ascribed it to the torsional vibration of cellulose molecules. Bernier et al.[6] found the two major temperature relaxations, and suggested that the transition at 260°K may be associated with the motion of small molecular segments under the stress and that the relaxation beginning beyond 400°K is associated with the cooperative movement of large segments of the structures.

In previous paper[8], it has been described that the dielectric and mechanical absoptions in high frequency range at low temperature are ascribed to the motion of CH_2OH groups in the disordered region of wood substance.

From these results in L-direction, it may be considered that the dispersion beginning below 10^{-2} Hz is due to the movement of rather large segments of the structures.

As it is reported that the dielectric dispersions correspond generally to the mechanical ones, the mechanical dispersion above 10^2 Hz would associate with the motion of CH_2OH groups in the non-crystalline region of wood substance[8]. However, as the mechanical dispersions do not always correspond to the dielectric ones, the motion of the other side chains which are not dielectrically active may also be involved in this relaxation.

Fig. 3 shows the frequency dependences of $\tan\delta$ in R- and T- directions. The similar tendency was observed in both directions. In high frequency range, the values of $\tan\delta$ for wood of low density increased with increasing frequency, while

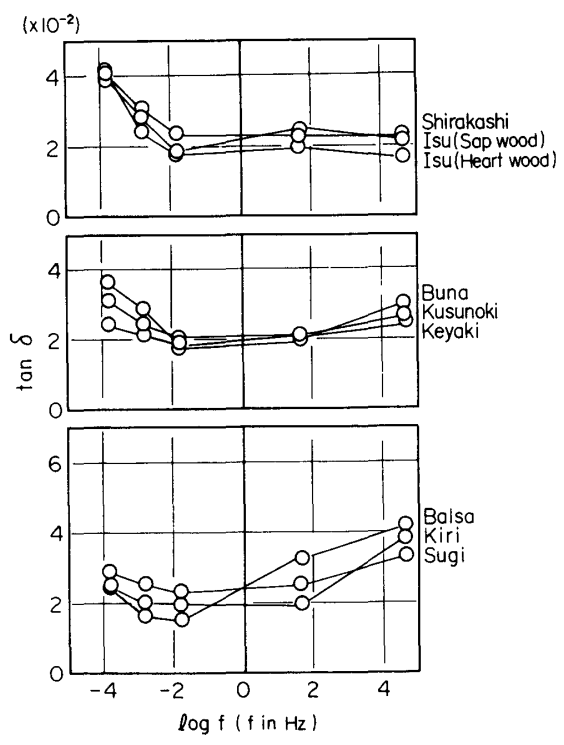

Fig. 3 (a). $\tan\delta$ as a function of frequency in radial direction.

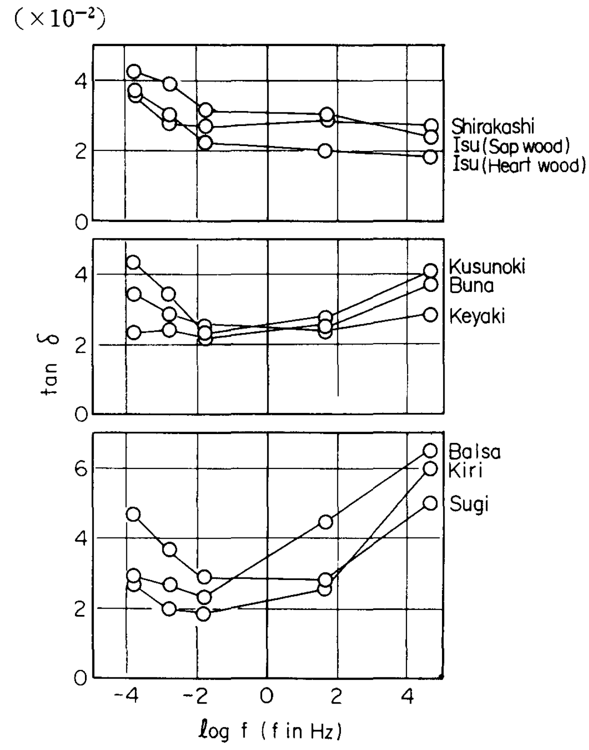

Fig. 3 (b). $\tan\delta$ as a function of frequency in tangential direction.

that of high density was independent of it.

2. *The effects of specific gravity and grain angle on the dynamic mechanical properties of wood*

In Tables 2～4, specific gravity, moisture content and the dynamic properties of wood samples are shown.

2-1. The density dependences of the dynamic properties of wood

(1) The dynamic elastic modulus E'

Fig. 4 shows the relationship between E' and ρ at 60 kHz. The values of E'

Table 2(a). Specific gravity, moisture content and the dynamic properties of wood at 60 kHz (composite oscillator).
R-direction

Species	ρ	E' dyne/cm^2	tan δ	E'' dyne/cm^2	M.C. %
Balsa	0 08	0.22×10^{10}	4.21×10^{-2}	0.92×10^{8}	5.3
Kiri	0.27	0.64	3.83	2.67	5.8
Sugi (Sapwood)	0.34	0.87	3.33	2.85	6.9
Nezuko	0.42	1.74	2.57	4.47	7.0
Kusuoki	0.45	1.53	3.02	4.56	8.6
Shiinoki	0.49	1.56	3.72	5.77	6.1
Karamatsu	0.50	1.75	3.19	5.38	8.4
Hoonoki	0.50	1.33	3.46	4.57	
Yamaguruma	0.50	1.94	3.32	6.39	
Hinoki	0.52	1.43	3.77	5.37	7.7
Tsuga	0.53	2.09	2.91	6.08	5.6
Kuri	0.53	1.58	3.37	5.31	6.5
Buna	0.54	1.87	3.03	5.66	6.3
Mizuki	0.60	1.83	3.33	6.08	6.7
Aogiri	0.61	1.85	3.28	6.01	5.9
Uwamizuzakura	0.66	2.19	3.01	6.61	5.9
Harunire	0.70	2.17	2.72	5.92	5.6
Keyaki	0.70	2.44	2.68	6.53	6.0
Yachidamo	0.75	2.38	2.75	6.57	6.6
Konara	0.81	2.68	2.73	7.32	5.9
Mizume	0.82	2.92	2.49	7.25	5.6
Shirakashi	0.82	3.16	2.27	7.23	6.1
Isunoki (Sapwood)	0.94	3.61	2.19	7.91	6.7
Burman timber	0.95	3.16	2.21	6.98	7.5
Burman timber	1.05	3.96	1.87	7.37	6.0
Isunoki (Heartwood)	1.08	4.50	1.72	7.70	7.3
Gray birch	1.11	3.81	2.20	8.31	9.5
Shimakokutan	1.19	5.33	1.46	7.77	8.2
Shimakokutan	1.30	6.19	1.42	8.78	7.6

Table 2(b). Specific gravity and the dynamic properties of wood at 60 kHz (composite oscillator).
T-direction

Species	ρ	E' dyne/cm^2	$\tan\delta$	E'' dyne/cm^2
Balsa	0.07	0.07×10^{10}	6.50×10^{-2}	0.44×10^{8}
Kiri	0.24	0.25	6.00	1.58
Sugi (Sapwood)	0.37	0.68	5.01	3.12
Nezuko	0.41	1.06	3.78	3.95
Hinoki	0.46	0.59	5.76	3.42
Ichii	0.45	0.76	3.85	2.88
Kusunoki	0.49	0.80	4.08	3.17
Shiinoki	0.50	0.57	5.03	2.83
Buna	0.51	0.82	3.71	3.06
Yamaguruma	0.51	1.10	4.19	4.60
Kuri	0.52	0.73	4.25	3.07
Karamatsu	0.57	0.99	4.29	4.24
Aogiri	0.58	0.88	3.72	3.25
Tsuga	0.53	1.36	3.48	4.67
Mizuki	0.59	1.06	3.48	3.57
Uwamizuzakura	0.65	1.38	2.84	3.94
Harunire	0.66	1.13	3.55	3.99
Keyaki	0.70	1.56	2.83	4.41
Yachidamo	0.76	1.52	2.95	4.48
Konara	0.79	1.38	3.17	4.35
Mizume	0.84	1.92	2.51	4.87
Shirakashi	0.82	1.54	2.71	4.18
Isunoki (Sapwood)	0.90	2.22	2.38	5.27
Isunoki (Heartwood)	1.06	3.16	1.85	5.84
Shimakokutan	1.29	5.24	1.41	7.29

for hardwood increased linearly with ρ in logarithmic scales regardless of the macroscopic structures such as diffuse porous, ring porous, semi-ring porous wood. The relation between E' and ρ obeys the logarithmic law. In T-direction the values of E' of softwood were larger than those of hardwood, while in R-direction there was no change in value of E' between softwood and hardwood. Since the cell arrangements of softwood are more regular than those of hardwood, it may be considered that the anisotropy of E' in R- and T-directions is not more remarkable in softwood than in hardwood.

Fig. 5 shows that E' versus ρ curves at 55～65 Hz have the same tendency as those at 60 kHz.

The values of E' and ρ at the intersecting point of regression lines in both directions, which represent probably these of wood substance, are shown in Table 5.

Table 3. Specific gravity and the dynamic properties of wood at 55~65 Hz (vibrating reed method).

R-direction

Species	ρ	E' dyne/cm^2	tan δ	E'' dyne/cm^2
Balsa	0.08	0.15×10^{10}	3.26×10^{-2}	0.62×10^{8}
Kiri	0.27	0.53	1.96	1.03
Sugi (Sapwood)	0.35	0.73	2.51	1.81
Kusunoki	0.46	1.22	2.02	2.46
Hinoki	0.50	1.07	2.06	2.18
Hoonoki	0.51	1.08	2.29	2.58
Akamatsu	0.53	1.41	2.09	2.95
Buna	0.58	1.37	2.10	2.88
Keyaki	0.75	2.24	2.09	4.69
Shirakashi	0.89	2.75	2.34	6.24
Isunoki (Sapwood)	0.95	3.04	2.40	7.29
Isunoki (Heartwood)	1.13	3.72	1.99	7.44

T-direction

Species	ρ	E' dyne/cm^2	tan δ	E'' dyne/cm^2
Balsa	0.10	0.04×10^{10}	4.44×10^{-2}	0.18×10^{8}
Kiri	0.27	0.19	2.57	0.49
Sugi (Sapwood)	0.35	0.43	2.77	1.17
Sugi (Heartwood)	0.38	0.56	2.80	1.58
Kusunoki	0.49	0.80	2.75	2.20
Hinoki	0.47	0.45	2.71	1.18
Hoonoki	0.55	0.69	2.53	1.74
Buna	0.53	0.60	2.42	1.45
Keyaki	0.71	1.50	2.52	3.77
Shirakashi	0.86	1.51	2.87	4.36
Isunoki (Sapwood)	0.93	1.79	3.02	5.39
Isunoki (Heartwood)	1.04	2.46	2.03	4.95

(2) The dynamic loss modulus E''

Fig. 6 shows the correlation between E'' and ρ at 60 kHz. The values of E'' of hardwood in T-direction increased linearly with increasing ρ in linear scale up to $\rho=1.3$. On the other hand, the values of E'' in R-direction increased linealy with ρ up to $\rho=0.7$ and then remained almost constant above $\rho=0.7$. In the same way as the case of E', the value of E'' in R-direction may coincide with that in T-direction at $\rho=1.6$. The effect of extractives on E'' will be discussed in section 3.

The relation between E'' and ρ for softwood and hardwood could be reprerented by the same regression line in R-direction, but not in T-direction. The anisotropy of E'' in both directions is more unremarkable in softwood than in hardwood.

Table 4(a). Specific gravity, moisture content and the dynamic properties of wood at 10~1000 sec (tensile stress relaxation).

R-direction

Species	M.C. %	ρ	10 sec			100 sec			1000 sec		
			E' dyne/cm^2	$\tan\delta$	E'' dyne/cm^2	E' dyne/cm^2	$\tan\delta$	E'' dyne/cm^2	E' dyne/cm^2	$\tan\delta$	E'' dyne/cm^2
Balsa	6.9	0.08	1.04×10^9	1.49×10^{-2}	0.16×10^8	1.02×10^9	1.66×10^{-2}	0.17×10^8	0.99×10^9	2.47×10^{-2}	0.24×10^8
Kiri	6.5	0.28	4.31	1.97	0.85	4.19	2.02	0.85	4.07	2.51	1.02
Sugi (Sapwood)	9.5	0.36	4.84	2.32	1.12	4.67	2.55	1.19	4.50	2.90	1.30
Sugi (Heartwood)	9.3	0.40	5.96	2.91	1.74	5.70	3.43	1.96	5.40	3.36	1.81
Hinoki	7.5	0.45	7.30	2.09	1.52	7.07	2.26	1.60	6.84	2.95	2.01
Kusunoki	9.8	0.47	8.62	1.89	1.63	8.32	2.91	2.42	7.93	3.64	2.99
Hoonoki	8.9	0.52	8.61	2.37	2.04	7.88	2.86	2.25	7.55	3.06	2.31
Akamatsu	9.3	0.54	7.81	2.09	1.63	7.55	2.76	2.09	7.22	3.68	2.66
Buna	9.2	0.57	1.06×10^{10}	1.98	2.10	1.05×10^{10}	2.46	2.53	9.89	3.13	3.09
Keyaki	7.9	0.73	1.01	1.88	1.91	0.98	2.16	2.11	9.48	2.45	2.32
Shirakashi	8.1	0.90	1.43	2.38	3.34	1.37	3.09	4.25	1.31×10^{10}	4.11	5.38
Isunoki (Sapwood)	8.4	0.95	1.50	1.90	2.86	1.45	2.88	4.17	1.38	3.96	5.46
Isunoki (Heartwood)		1.09	1.58	1.79	2.83	1.52	2.44	3.71	1.47	4.15	6.09

Table 4(b). Specific gravity, moisture content and the dynamic properties of wood at 10~1000 sec (tensile stress relaxation).

T-direction

Species	M.C. %	ρ	10 sec			100 sec			1000 sec		
			E' dyne/cm^2	tan δ	E'' dyne/cm^2	E' dyne/cm^2	tan δ	E'' dyne/cm^2	E' dyne/cm^2	tan δ	E'' dyne/cm^2
Balsa	6.5	0.11	0.30×10^9	2.32×10^{-2}	0.07×10^8	0.29×10^9	2.65×10^{-2}	0.07×10^8	0.28×10^9	2.90×10^{-2}	0.08×10^8
Kiri	6.0	0.20	1.94	1.84	0.36	1.89	1.97	0.37	1.83	2.72	0.50
Sugi (Sapwood)	9.4	0.34	3.19	2.87	0.91	3.03	3.66	1.11	2.85	4.68	1.28
Sugi (Heartwood)	8.5	0.38	3.48	3.89	1.35	3.23	4.27	1.40	3.12	3.57	1.11
Hinoki	8.5	0.45	2.82	2.69	0.76	2.70	3.07	0.83	2.58	3.07	0.79
Kusunoki	10.4	0.49	5.65	2.31	1.31	5.43	3.44	1.87	5.15	4.35	2.23
Akamatsu	8.9	0.52	3.69	2.39	0.88	3.54	3.28	1.16	3.35	4.21	1.41
Hoonoki	8.9	0.54	5.23	2.37	1.24	5.05	2.90	1.47	4.85	3.41	1.65
Buna	8.4	0.51	4.39	2.52	1.10	4.23	2.86	1.21	4.05	3.44	1.39
Keyaki	8.5	0.71	8.53	2.18	1.86	8.23	2.40	1.98	7.91	2.35	1.86
Shirakashi	7.6	0.87	9.22	2.70	2.49	8.86	3.13	2.77	8.40	3.57	3.00
Isunoki (Sapwood)	8.5	0.97	1.01×10^{10}	3.17	3.19	9.59	3.92	3.76	9.03	4.27	3.85
Isunoki (Heartwood)		1.07	1.41	2.26	3.18	1.36×10^{10}	3.10	4.22	1.28×10^{10}	3.71	4.75

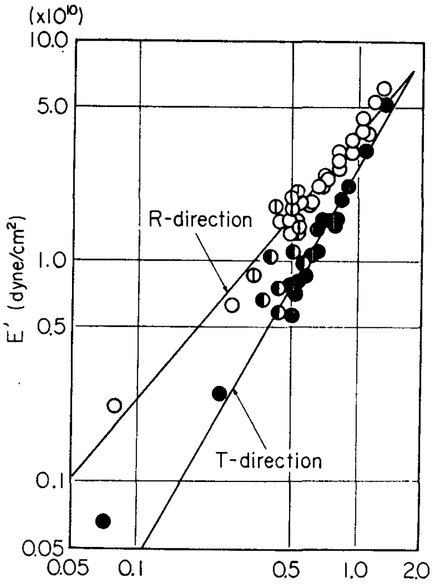

Fig. 4. The relation between E' and ρ in the transverse direction at 60 kHz. ○ hardwood in R-direction, ⦶ softwood in R-direction, ● hardwood in T-direction, ◐ softwood in T-direction.

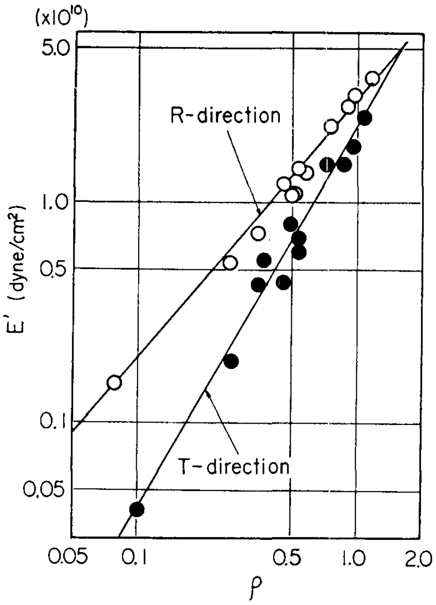

Fig. 5. The relation between E' and ρ in the transverse direction at 55~65 Hz.

Table 5. The regression lines and the values of the correlation coefficient of the dynamic elastic modulus of wood E' as a function of specific gravity. The values of E' and ρ at the intersected point of the regression lines in R- and T-direction.

	Vibrating reed 55~65 Hz	Composite oscillator 60 kHz
Regression line and correlation coefficient γ		
R-direction	$E'=2.90\times10^{10}\times\rho^{1.17}$ $\gamma=0.990$	$E'=3.66\times10\times\rho^{1.19}$ $\gamma=0.988$
T-direction	$E'=2.17\times10^{10}\times\rho^{1.73}$ $\gamma=0.982$	$E'=2.59\times10^{10}\times\rho^{1.77}$ $\gamma=0.976$
The values of E' and ρ at the intersected point of the regression lines in R- and T-directions.		
E'	5.35×10^{10} dyne/cm^2	7.27×10^{10} dyne/cm^2
ρ	1.68	1.78

Figs. 7 and 8 show the relations between E'' and ρ at 55~65 Hz, 10 and 1000 sec. The values of E'' in both directions increased linearly with ρ up to $\rho=1.0$.

(3) The loss tangent $\tan\delta$

The relationship between $\tan\delta$ and ρ at 60 kHz is shown in Fig. 9. The loss tangent could be represented by the same regression line for both softwood and

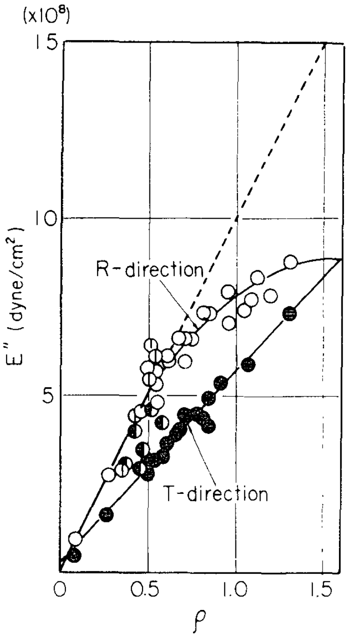

Fig. 6. The relation between E'' and ρ in the transverse direction at 60 kHz. ○ hardwood in R-direction, ◐ softwood in R-direction, ● hardwood in T-direction, ◐ softwood in T-direction.

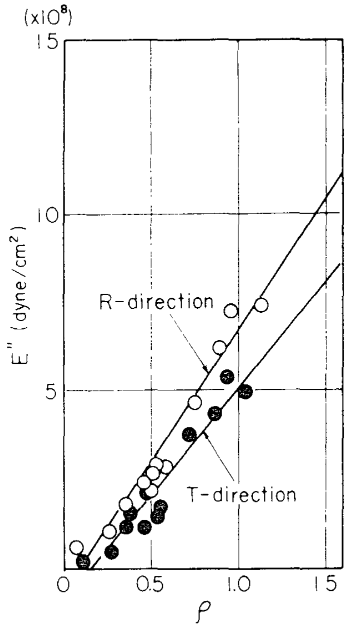

Fig. 7. The relation between E'' and ρ in the transverse direction at 55~65 Hz.

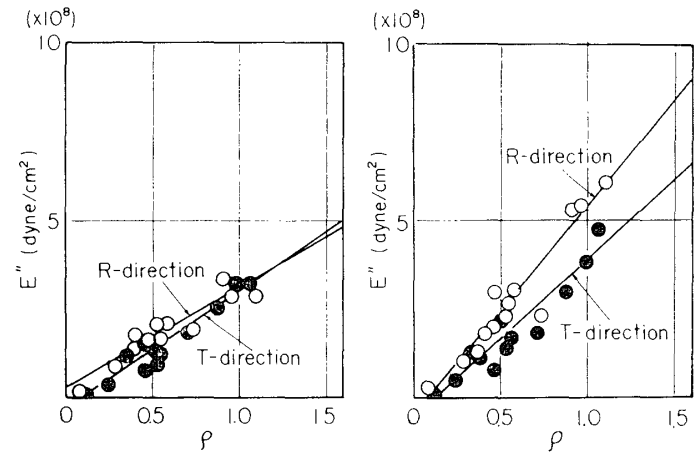

Fig. 8. The relation between E'' and ρ in the transverse direction at 10 sec (left figure) and 1000 sec (right figure).

hardwood. The values of tan δ in R-direction decreased linearly with ρ over the whole range of ρ studied, while those in T-direction were larger than those in R-direction below $\rho=1.0$. The difference of the values of tan δ in both directions is probably due to the different anatomical structures of wood as stated in the discussion on E'.

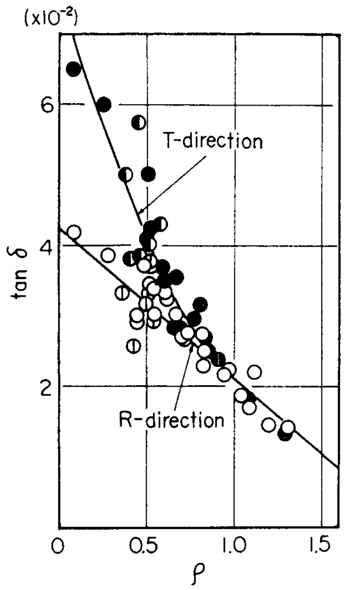

Fig. 9. The relation between tan δ and ρ in the transverse direction at 60 kHz. ○ hardwood in R-direction, ⦶ softwood in R-direction, ● hardwood in T-direction, ◐ softwood in T-disection.

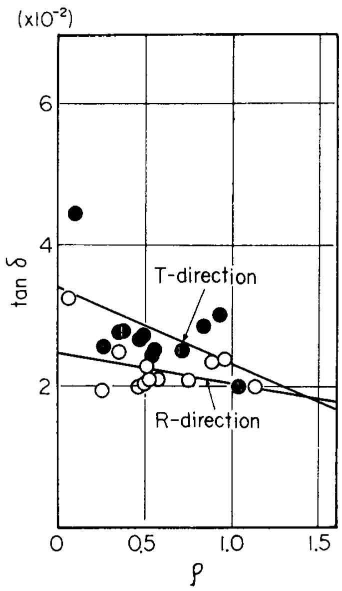

Fig. 10. The relation between tan δ and ρ in the transverse direction at 55~65 Hz.

From Figs. 9 and 10 showing the relation between tan δ and ρ at 55~65 Hz and 60 kHz, it is obvious that tan δ at 55~65 Hz does not strongly depend on ρ compared with that at 60 kHz.

MATSUMOTO[9] studied the relation between ρ and logarithmic decrement for Sugi in L-direction at 600 Hz and explained that the decrease of tan δ with ρ is

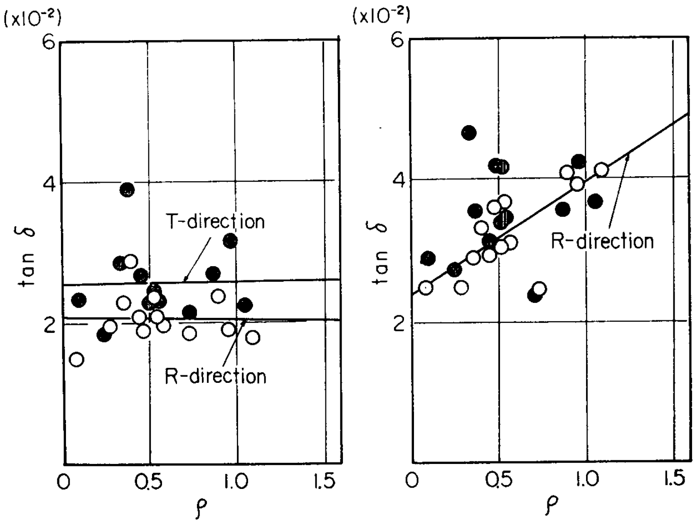

Fig. 11. The relation between tan δ and ρ in the transverse direction at 10 sec (left figure) and 1000 sec (right figure).

due to the increase in amount of summer wood having small fibril angle.

The relations between $\tan\delta$ and ρ at 10 and 1000 sec are shown in Fig. 11. At 10 sec the value of $\tan\delta$ was independent of ρ, whereas at 1000 sec the value increased with ρ.

The relations between the dynamic properties in L-direction and specific gravity at 60 kHz are shown in Fig. 12. The value of E' and E'' increased linealy with ρ in linear scale, while the value of $\tan\delta$ decreased linealy with ρ.

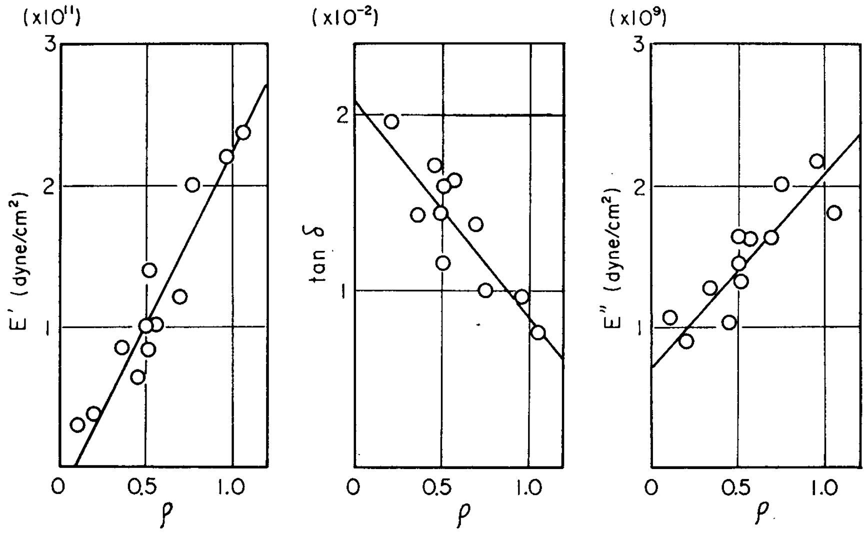

Fig. 12. The relation between E', $\tan\delta$, E'' and ρ in longitudinal direction at 60 kHz.

2-2 The effect of the grain angle in RT plane on the dynamic properties of wood

In this section, the effect of grain angle on the dynamic properties at 60 kHz is examined. The results are shown in Figs. 13 to 15.

E' had the smallest value at the grain angle of 45 degree in Sugi, and it decreased in magnitude with increasing grain angle in hardwood except Kiri[10,11]. The value of E'' decreased generally with increasing grain angle in RT plane. The value of $\tan\delta$ took its maximum at 45 degree in wood of low specific gravity, while the maximum could not be observed remarkably in wood of high specific gravity.

3. The influence of the extraction on the dynamic mechanical properties of wood

As stated in section 2, the values of E'' increased linearly with ρ in the range of low density and then became constant in the range of high density in R-direction. As it is considered that dense wood contains much amount of extractives, the effect of the extraction on dynamic properties was studied in this section. The samples were extracted with hot water for about two weeks and then with the

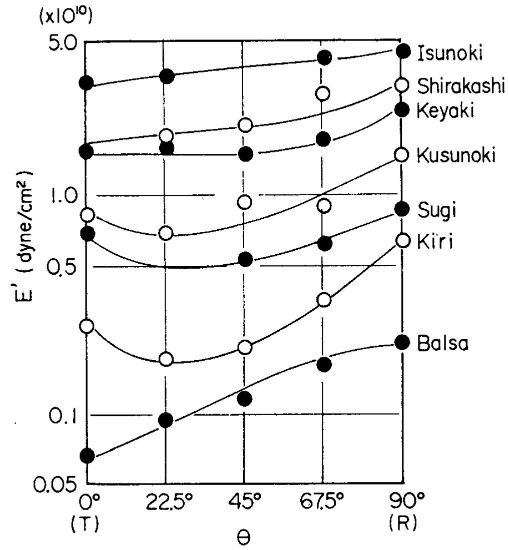

Fig. 13. The effect of grain angle θ on E' in RT plane at 60 kHz.

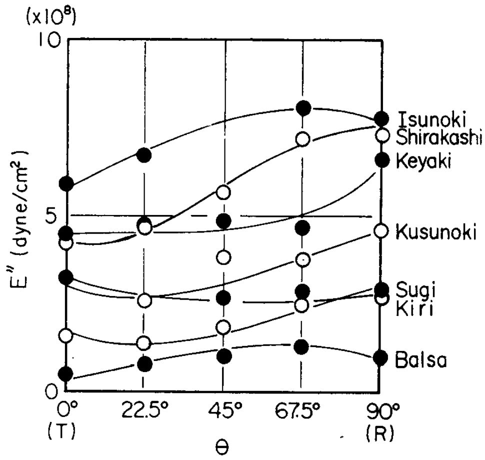

Fig. 14. The effect of grain angle θ on E'' in RT plane at 60 kHz.

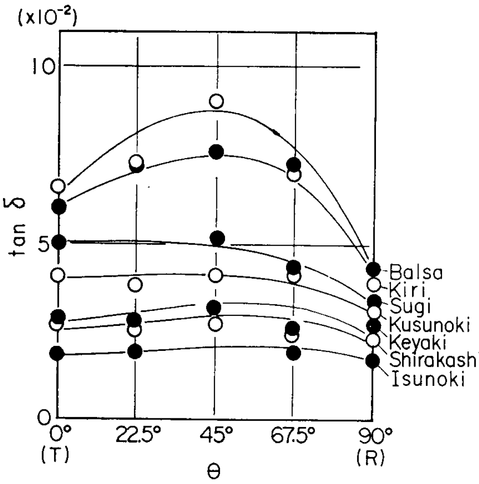

Fig. 15. The effect of grain angle θ on $\tan\delta$ in RT plane at 60 kHz.

mixture of alcohol and benzene (1 : 2) for about two weeks. The collapse was observed in hardwood of low density by the extraction. The results at 60 kHz are shown in Table 6.

The curves of E', $\tan\delta$ and E'' vs. ρ for the untreated and the extractived wood in R-direction are shown in Figs. 16~18. The value of E' decreased by the extraction, and this results agreed very well with CHOPRA's results[12], but did not with NARAYANAMURTI's[13]. The considerable decrease in the value of E' of Kiri may mainly result from collapse or crack of microscopic structure.

E'' and $\tan\delta$ were not influenced by the extraction in the range of high

Table 6. The effect of extraction on the dynamic properties of wood in R-direction.

Species	ρ	E' dyne/cm^2	$\tan\delta$	E'' dyne/cm^2
Kiri	0.25	0.24×10^{10}	6.28×10^{-2}	1.58×10^{8}
Sugi (Sapwood)	0.33	0.88	4.61	4.10
Kusunoki	0.44	1.21	4.31	5.21
Hoonoki	0.45	1.16	3.69	4.29
Hinoki	0.52	1.28	4.57	5.83
Buna	0.54	1.75	3.45	6.01
Keyaki	0.67	1.69	3.26	6.07
Shirakashi	0.79	2.24	2.59	5.86
Isunoki (Sapwood)	0.91	3.45	2.01	6.94
Isunoki (Heartwood)	1.06	3.73	2.10	7.87

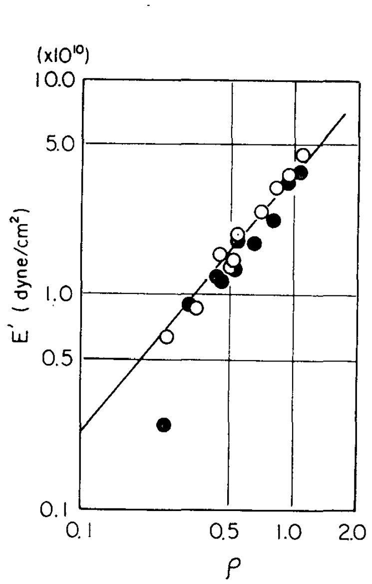

Fig. 16. The relation between E' and ρ in radial direction at 60 kHz. The open circles and solid line represent the untreated wood, and the closed circles represent the extracted wood.

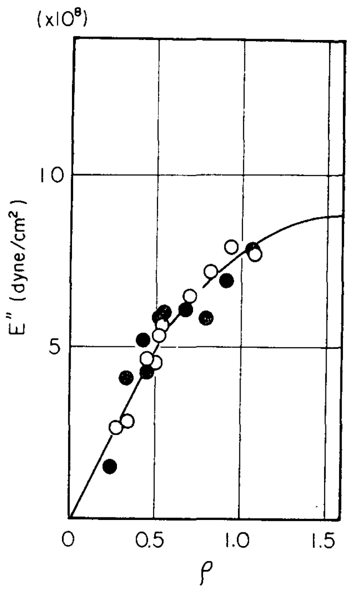

Fig. 17. The relation between E'' and ρ in radial direction at 60 kHz. The open circles and solid line represent the untreated wood, and the closed circles represent the extracted wood.

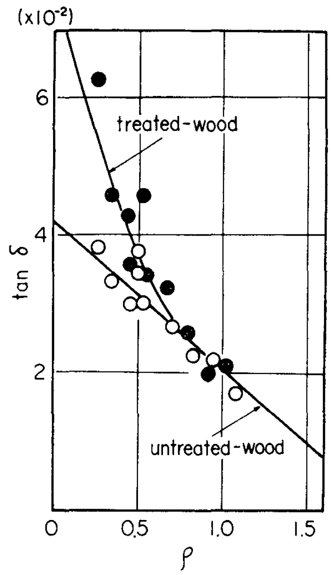

Fig. 18. The relation between $\tan\delta$ and ρ in radial direction at 60 kHz. The open circles and linear line represent the untreated wood, and the closed circles and curved line represent the extracted wood.

density. However, the values of $\tan\delta$ increased remarkably in the range of low density and this may result from collapse or crack mentioned above.

4. On the dynamic properties of wood used for the musical instruments

The dynamic properties of wood used for the musical instruments as a function of specific gravity or annual ring width are discussed in this section. Sitka spruce *(Picea sitchensis* Carr.) and Yezo spruce *(Picea jezoensis* Carr.) are used as resonance and key boards and maple (*Acer mono* MAXIM. var. *eupictum* NAKAI) as action and bridge materials of piano.

(1) The comparison of the dynamic properties of wood used for the musical instruments with those of other wood

The results are shown in Figs. 19 to 21. The values of E' and E'' for Sitka spruce and Yezo spruce in L-direction were larger than those of other wood, while the values of $\tan\delta$ were lower than those of various other wood species. On the contrary the properties of maple were same as those of other species.

(2) The effect of annual ring width on dynamic properties

The results of Sitka spruce are shown in Figs. 22~24. The values of E' and E'' increased with decreasing annual ring width regardless of directions. The values of $\tan\delta$ increased in T-direction and decreased in R-direction with decreasing annual ring width respectively and were independent of it in L-direction. These results on E' and $\tan\delta$ were similar to those of spruce reported by FUKADA[14] and TATEMITI[7].

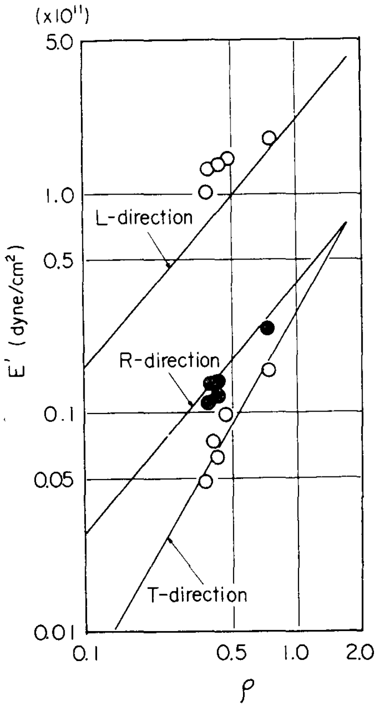

Fig. 19. The relation between E' and ρ at 60 kHz. The circles represent the wood used for the musical instruments, and solid lines represent regression lines of Figs. 4 and 12.

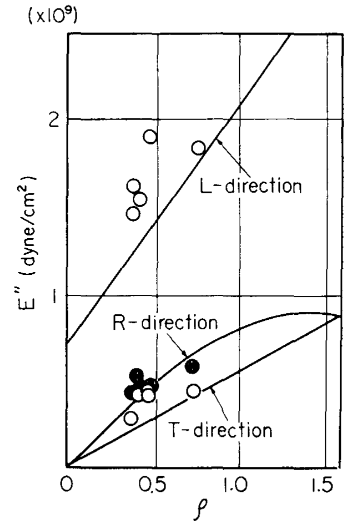

Fig. 20. The relation between E'' and ρ at 60 kHz. The circles represent the wood used for the musical instruments, and solid lines represent regression lines of Figs. 6 and 12.

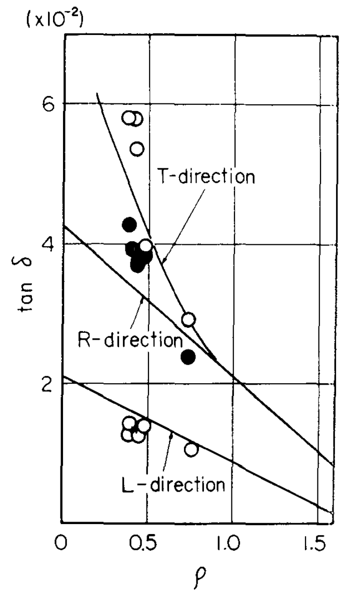

Fig. 21. The relation between $\tan\delta$ and ρ at 60 kHz. The circles represent the wood used for the musical instruments, and solid lines represent regression lines of Figs. 9 and 12.

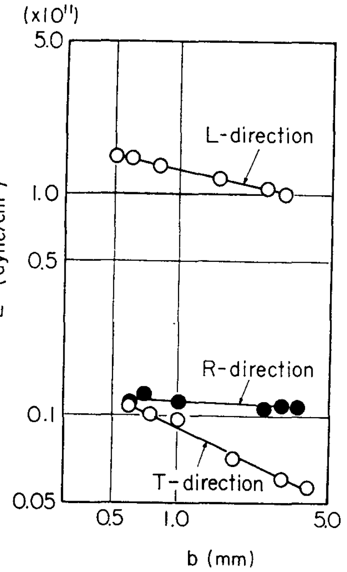

Fig. 22. The dependence of the annual ring width b on E' of Sitka spruce at 60 kHz.

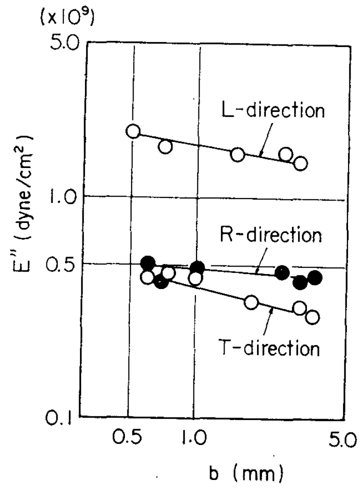

Fig. 23. The dependence of the annual ring width b on E'' of Sitka spruce at 60 kHz.

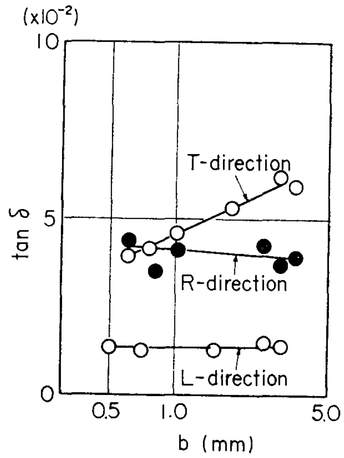

Fig. 24. The dependence of the annual ring width b on $\tan\delta$ of Sitka spruce at 60 kHz.

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